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In this program,. we have developed the ability to microfabricate optical devices with feature sizes significantly smaller than the wavelength of light, and use these to control light within very small geometries. Although structures with similar lateral dimensions have been made by electron beam lithography for over 20 years now, it has only recently become possible to transfer such patterns into semiconductors with a high enough quality to produce "photonic nanostructures" in materials systems with a large refractive index contrast. Through our improved processing capabilities, it is now possible to efficiently localize light and thereby miniaturize the lateral sizes of optical devices.

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In this program, we have developed the ability to microfabricate optical devices with feature sizes significantly smaller than the wavelength of light, and use these to control light within very small geometries. Although structures with similar lateral dimensions have been made by electron beam lithography for over 20 years now, it has only recently become possible to transfer such patterns into semiconductors with a high enough quality to produce "photonic nanostructures" in materials systems with a large refractive index contrast. Through our improved processing capabilities, it is now possible to efficiently localize light and thereby miniaturize the lateral sizes of optical devices.

Using this enabling technology, we have started to construct planar photonic crystal integrated circuits, and to improve the efficiency of light emitters. The proposed devices rely on the synergies between several technologies. One such example is the development of surface plasmon enhanced light-emitting diodes, which promise to be extremely fast and efficient light emitters. Designs for our plasmon enhanced light sources combine metal-mirror vertical cavities with patterned metallic surface layers which can efficiently couple out the light from the semiconductor by exciting surface plasmons. Detailed three-dimensional electromagnetic modeling permits us to design and optimize the precise geometries of such devices on paper prior to microfabrication. High Q cavities fabricated in photonic crystals also lend themselves to the construction of extremely efficient, fast miniature laser sources. We have recently demonstrated that it is possible to construct lasers with photonic crystal mirrors, in which the emission wavelength, polarisation and direction are all controlled entirely by the fabricated geometry of the nanocavity. We intend to connect these lasers and form complex networks in which light can be routed, switched and filtered within very compact photonic circuits.

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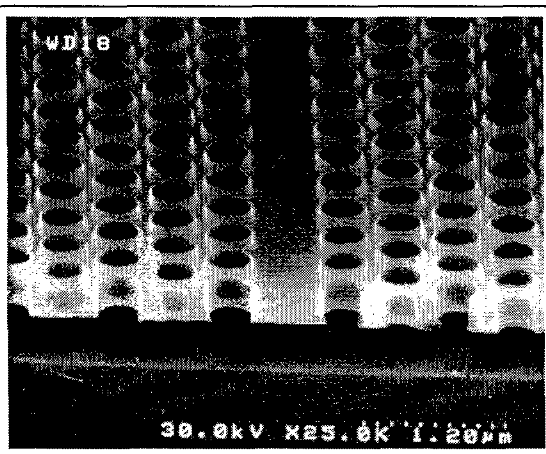


The possibility of miniaturizing optical devices brings with it many benefits with regard to the modulation speed, efficiency, and the feasibility of large-scale integration. For example, photonic crystal lasers, with mode volumes of approximately 0.03 cubic microns, support only one mode which has to be pumped to overcome lasing threshold. This compares to thousands of modes which have to be pumped in conventional semiconductor lasers in order to reach threshold. Thus, it is expected that the photonic crystal lasers can be modulated at much higher frequencies and requires much lower lasing threshold currents than conventional lasers. By controlling the power dissipation and mode volume, photonic crystal cavities also make it possible to confine the light and to reduce the footprint of individual lasers to about a square micrometer. This enables the integration of many devices on a laser chip. Devices within a photonic circuit can be connected with optical waveguides, and we have therefore developed photonic crystal waveguides. Such guides allow light to be transmitted around very sharp bends without the usually associated bend

losses. So far we have demonstrated efficient guiding of 1.5 micron light through 0.4 micron wide photonic crystal waveguides (Figure 1) and around 60 degree bends.

Originally, our effort in photonic crystal devices was focussed on the use of semiconductors as both light sources and mirrors, making use of the high refractive index contrast available from most semiconductors. More recently, our effort on developing highly efficient light sources has also included the use of patterned metal layers to couple light from a semiconductor into air. It is possible to generate surface plasmons at the interface between semiconductor and metal layers, and energy can be emitted from such plasmons into free space by introducing a grating into the metal surface layer. Recently, we have observed highly efficient light extraction from such plasmon-enhanced light-emitting diode structures, leading us to believe that light emitting diodes with external quantum efficiencies of above 80% may be constructed. We observe a 60-fold increase in the light emission from a fully fabricated surface plasmon enhanced LED over the unprocessed semiconductor emitter, which we expected to have a 2% extraction efficiency. This enormous increase in the light extraction efficiency will enable the development of very efficient light sources for displays, and the surface metal can serve the dual function as electrical contact and surface plasmon coupling layer. Another advantage of our surface plasmon light emitting diode design relies on the use of a very short optical cavity, which results in an increase of the spontaneous emission rate and a corresponding increase in the speed of the light-emitting diode. We expect these diodes to also be useful as very fast sources for fiber communication networks, especially when the coherence provided by a laser beam is not required. Surface plasmon enhancement devices can be designed for wavelengths ranging from the deep-uv wavelength range to the near-IR spectral range.

Research Concentration Areas:

Quantum Dot Nanocavity Lasers: The combination of high Q nanocavities with quantum dot emitters is expected to enable extremely efficient and fast light sources. The combined photonic and electronic confinement to dimensions comparable to their respective wavelengths enables the coherent control of the light-matter interaction and paves the way for a new nanophotonic device technology for systems capable of quantum information exchange. The cavity size in recently demonstrated planar photonic band-gap (PBG) "defect" resonators has been reduced through lithography to obtain optical mode volumes of only a few cubic half-wavelengths in the semiconductor. This is conservatively 10-20 times smaller than the smallest oxide aperture VCSEL cavities reported to date. The in-plane band-gap also eliminates the guided modes present in VCSEL cavities. This results in a cavity which is for all practical purposes truly single mode with very little coupling to leaky modes (β-factor ~ 100%). Apart from their tiny mode volumes, these planar resonators can also be naturally integrated with photonic crystal input/output waveguides, thus allowing very accurate and flexible "monitoring" of the optical system. The challenge for such photonic crystal nanocavities is to increase the optical mode quality factor to make it competitive with other optical cavities such as VCSELs or microspheres. Theoretically, such planar cavities should be able to reach Q values as large as 20,000 (or higher), but experimentally demonstrated cavity Q's have been limited to 1,000-2,000 so far due mainly to fabrication issues. Further work on optimized cavity geometries needs to be done to clarify whether or not these PBG cavities can play an important role in strongly coupled systems. Hybrid VCSEL-PBG cavities (so-called 2D+1D cavities) should also be investigated in order to obtain the smallest volume along with the highest Q. Spin-offs of such work are very broad and include dense multi-wavelength laser arrays on a monolithic wafer, reduced threshold lasers, advances in high speed lasers and detectors, low power micro-optical interconnects, and high efficiency LEDs for illumination and display technology.

Through the fabrication of such high-Q nanocavities and the growth of quantum dots, it is now possible to mimic the well-known vacuum Rabi oscillator, in which the Jaynes-Cumming-ladder spectral splitting (or oscillation frequency) depends directly on the photon number in the cavity (or excitation level). This type of cavity QED photon/exciton quantum entanglement provides the key step for quantum computing. To achieve strong coupling with a single quantum dot, having an excited state lifetime τ, in a nanocavity with optical mode volume V, photon decay rate κ, and quality factor Q, the splitting $2g_0$ needs to exceed κ. (Typically the dipole dephasing rate γ at low temperatures is smaller than κ, so this is not the main problem.) One can easily show that $2g_0/\kappa$ is proportional to Q divided by the square root of the product τV. Although strong coupling based on self-organized quantum dots has been considered before, the cavity volumes required for the strong coupling were prohibitively small for the $\tau \approx 1$ ns typical lifetime. Today, the nanocavities based on "point defects" within 2D photonic crystals demonstrated by our group can achieve the necessary mode volumes; remarkably, V is 100 times smaller than that of previous native-oxide 2-μm-aperture nanocavities, while it is still possible to retain a Q of a few thousand.

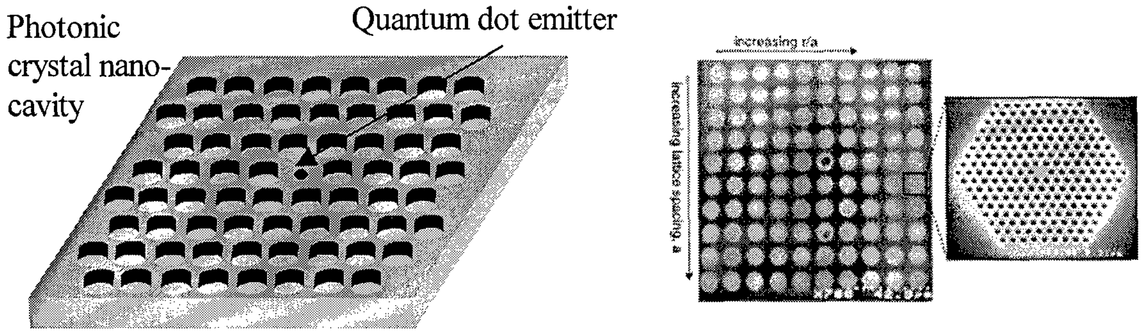


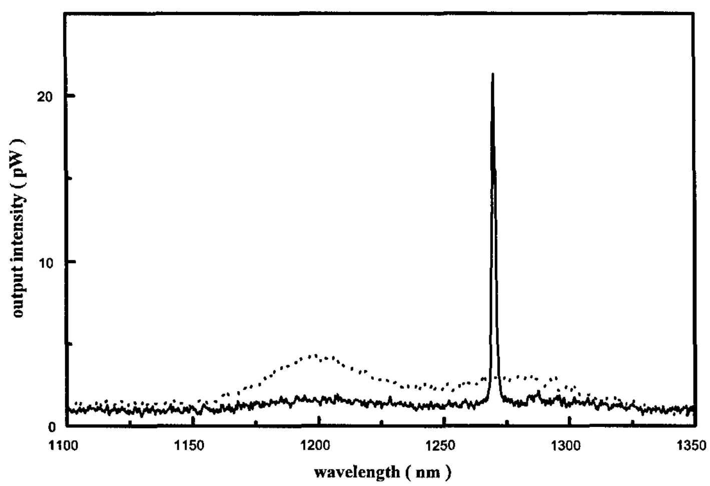
Figure 1 Photonic crystal nanocavity with an active region containing self-organized quantum dots. Also shown is a typical array of nanocavities that allows the lithographic coarse tuning of the resonance peak.

Figure 1 is a schematic of a 2D photonic crystal nanocavity, which can be fabricated using electron beam lithography and reactive-ion-etching to form the holes that lead to Bragg scattering within the 2D waveguide and result in the 2D photonic bandgap. A critical feature of this cavity is that it enables optical confinement to a mode volume of $\approx 2.5(\lambda_0/2n)^3$, where λ_0/n is the wavelength in the semiconductor. We have already demonstrated room temperature lasing in the smallest optical cavities, with mode volumes down to $2.5(\lambda_0/2n_{slab})^3$, or 0.03 μm^3 in InGaAsP emitting at $\lambda_0 = 1.55$ μm. They have also been able to tune the emission wavelength of these lasers from 1450 to 1620 nm within a 10×10 laser array in an area of 100 μm$\times$100 μm by local lithographic modification of the cavity lengths. As the mode volumes of nanocavities are decreased, the coupling efficiency between the spontaneous emission within the cavity and the lasing mode can be significantly improved. We have calculated coupling factors (β) above 85% for optimized photonic crystal lasers constructed in active quantum well material. This spontaneous emission coupling efficiency can be even higher if the linewidth of the semiconductor emission is narrowed, as is the case when using quantum dot active material. Therefore, single defect photonic crystal lasers represent in many ways the ultimate evolution of VCSELs, as control over both vertical and lateral spontaneous emission is possible. With most of the spontaneous emission funneled into a single optical mode, the photonic crystal laser can be modulated at much higher frequencies even close to threshold. The photonic crystal provides us

with the unique opportunity of coupling light emitted by one cavity, and using it to optically pump another with negligible diffraction losses. Photonic crystals provide us with the opportunity of constructing very compact laser sources with designed frequencies and polarization as well as wavelength and polarization sensitive detector arrays. Moreover, they can form very flexible platforms for connecting optical sources, detectors, routers, modulators, polarizers and filters in very compact microfabricated systems. Clearly many of these possibilities and advantages of photonic crystals will carry over to quantum entanglement devices.

The growth of quantum dots by epitaxial growth usually results in inhomogeneous broadening of the emission resulting from ensemble of InAs island sizes. For the ground state emission, the inhomogeneous broadening is typically as wide as 40meV and the lifetime is around 800psec in bulk at room temperature. However, the ground state emission from single QD (SQD) is narrower than 150μeV at 60K or less in the low excitation regime as observed by spatially resolved photoluminescence (PL) or μ-PL. Microcavities are expected to modify radiation process and thereby enhance spontaneous emission dramatically. In the coming year, we intend to use near field scanning optical microscopy (NSOM) to characterize and pump these devices, as this technique will enable us to also measure spatially resolved photo-luminescence (PL). The NSOM tip can be used to excite single quantum dot (SQD) locally as illumination mode and to pick up local field of emission from SQD as collection mode. The combination of an ultrafast laser system with NSOM is more informative than conventional μ-PL since the NSOM can obtain near-field information with as high resolution as 100nm or less while μ-PL has only micrometer resolution and generates only quasi-far field information This novel combination gives us further information of SQD emission process such as field distribution of mode, modal volume, emission lifetime and coupling efficiency of emission to the mode. The NSOM tip is scanned as collection mode on surface of cavity pumped by ultrafast laser. On the other hand, the ultrafast laser can pump SQD on center of cavity through NSOM tip as illumination mode and objective lens picks up far field pattern as well. This combination with NSOM is only the alternative to confirm modified radiation resulting from resonant mode with smallest modal volume.

Figure 2. Photoluminescence spectrum showing a sharp resonance peak measured from a nanocavity fabricated in quantum dot materal. The dotted line shows the emission spectrum from the unpuatterned quantum dot material



Photonic Crystal Waveguides: In-plane routing of light between optical elements requires waveguides. The high index contrast between Si and silicon dioxide allows the easy definition of

single mode slab waveguides. When combined with photonic bandgap mirrors, it is possible to include sharp bends within these waveguides allowing the compact integration of photonic components.

Plasmon Structures: Ultra-small optical cavities can be created by using the interaction between plasmon resonances from small metal structures which can concentrate light into extremely small volumes. If the light can be coupled out of the semiconductor emitter, the resulting nanocavities can give rise to significant enhancement in the spontaneous emission rates and enable the development of highly efficient and fast light-emitting diodes.

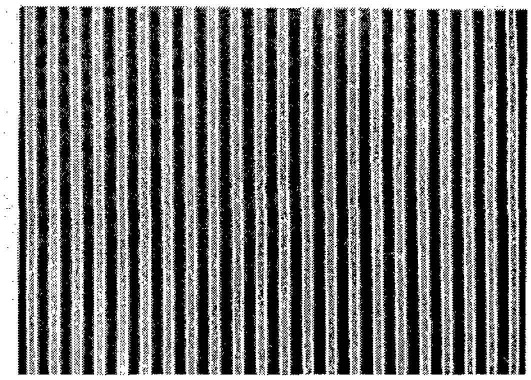


Figure 3. Scanning Electron Micrograph of a surface plasmon enhanced LED showing the metal grating pattern which is used to couple out the radiation.

We have demonstrated a method for enhancing the emission properties of light-emitting diodes, by coupling to surface plasmons. The analyzed structure consists of a 90nm thick semiconductor layer sandwiched between two silver films. A single 8nm thick InGaAs quantum well is positioned in the middle of the semiconductor membrane. The main emission peak is at the wavelength of 990nm, corresponding to conduction-to-heavy hole (C-HH) band transitions. Another peak can be observed at 930nm, corresponding to conduction-to-light hole (C-LH) band transitions. If a periodic pattern is defined in the top semitransparent metal layer by lithography (Figure 3), it is possible to efficiently couple out the light emitted from the semiconductor and to simultaneously enhance the spontaneous emission rate. For the analyzed designs, we theoretically estimate extraction efficiencies from this first design as high as 37% and Purcell factors (Fp) of up to 4.5. We have experimentally measured photoluminescence intensities of up to 46 times higher in fabricated structures compared to unprocessed wafers. The increased light emission is due to an increase in the efficiency and an increase in the pumping intensity resulting from trapping of pump photons within the microcavity. The measured photoluminescence spectra are shown in Figure 4. The spectra correspond to: (a) the unprocessed wafer; (b) the half-processed wafer (i.e. 90nm thick semiconductor membrane on top of a thick, nontransparent silver layer); (c) the unpatterned metal-clad microcavity (i.e. a semiconductor membrane sandwiched between two metal films,

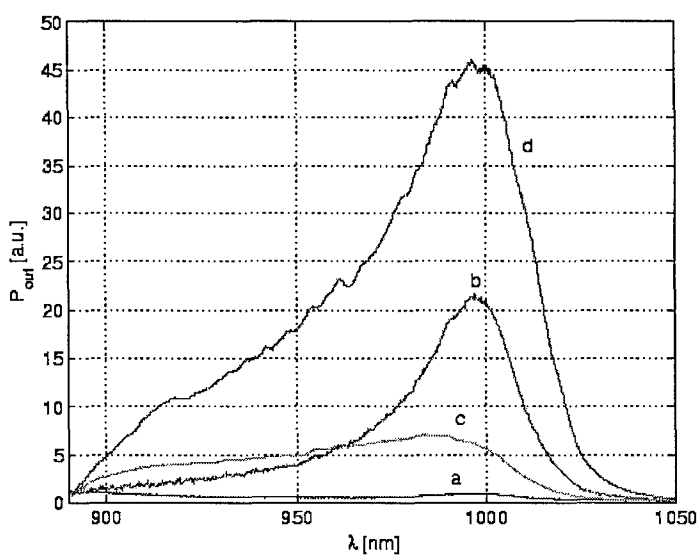


Figure 4. Luminescence spectra from a surface plasmon enhanced LED at various stages of fabrication (see text)

without patterning of the top silver layer) and (d) the fully processed structure (where silver stripes are defined in the top silver layer, with the grating periodicity of 250nm and the 160nm gap between silver stripes).

Surface plasmon LED designs such as the one demonstrated in this program will lead to highly efficient light emitting diodes, with quantum efficiencies approaching 100% and extremely high modulation speeds.